Final Report

Impact of Typhoons on the Western Pacific: Temporal and horizontal variability of SST cooling

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Long-term Goals/Scientific Background

The long term goal of this research has two themes: 1) To understand how upper ocean temperature gradient, initial mixed-layer depth, etc., contribute to hurricane-ocean interaction. With this understanding, we should be in position to make to make better forecasts of hurricane-ocean interaction, and especially of hurricane intensity. A new manuscript (described below) demonstrates an important aspect of this. And 2) to understand how the ocean recovers following a hurricane (tropical cyclone, TC) passage, emphasized here.

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Objectives

A specific question that came out of a study of satellite imagery during the CBLAST project was — What processes cause the cool SST in a hurricane wake to warm back toward pre-hurricane values? This SST warming (also called wake recovery) can be rapid. In the CBLAST Fabian case, the cool wake SST anomaly decayed (i.e., SST recovered back toward pre-hurricane values) with an e-folding time of about five days. In the CBLAST Frances case, the e-folding time was considerably longer, about two weeks.

Approach

A model of this surface layer warming process was developed under a previous ONR grant (Price et al., 2008) and can be tested rigorously with the ITOP field data set (discussed below). This model is built around two hypotheses. The first,

> H1) SST warming is a local process driven in the main by an anomalous air-sea heat flux (anomalous compared to regions outside the cool wake).

The heat flux over a cool wake is expected to be biased positive, typically by 40 - 80 W m^{-2}, simply because the SST in the wake is at first cooler than the surrounding regions (or summer conditions generally). This is a fairly direct inference from conventional air-sea heat flux parameterizations. The question then is – How can such a small heat flux produce the observed, rapid warming rate? The second hypothesis is that

> H2) The evident shallow trapping (storage) depth of this anomalous heat flux is determined not by the anomalous heat flux itself (which is small) but rather by the much larger amplitude diurnal cycle of the surface heat flux that is typical of post-hurricane weather (light winds and clear skies).

Work Completed/Results

The ITOP field phase observed several cases of wake warming with far greater detail of *in situ* ocean data than has ever been available before. Here we will consider the shipboard meteorology and ctd measurements made from R/V Revelle during the several week period following the passage of typhoon Fanapi (Chief Scientist Steven Jayne, WHOI, who is collaborating on this research).

A ctd section made six days after the passage of Fanapi (Figs. 1 and 2) shows that the warming was indeed trapped within the upper 5 - 15 m of the sea surface during the period of rapid

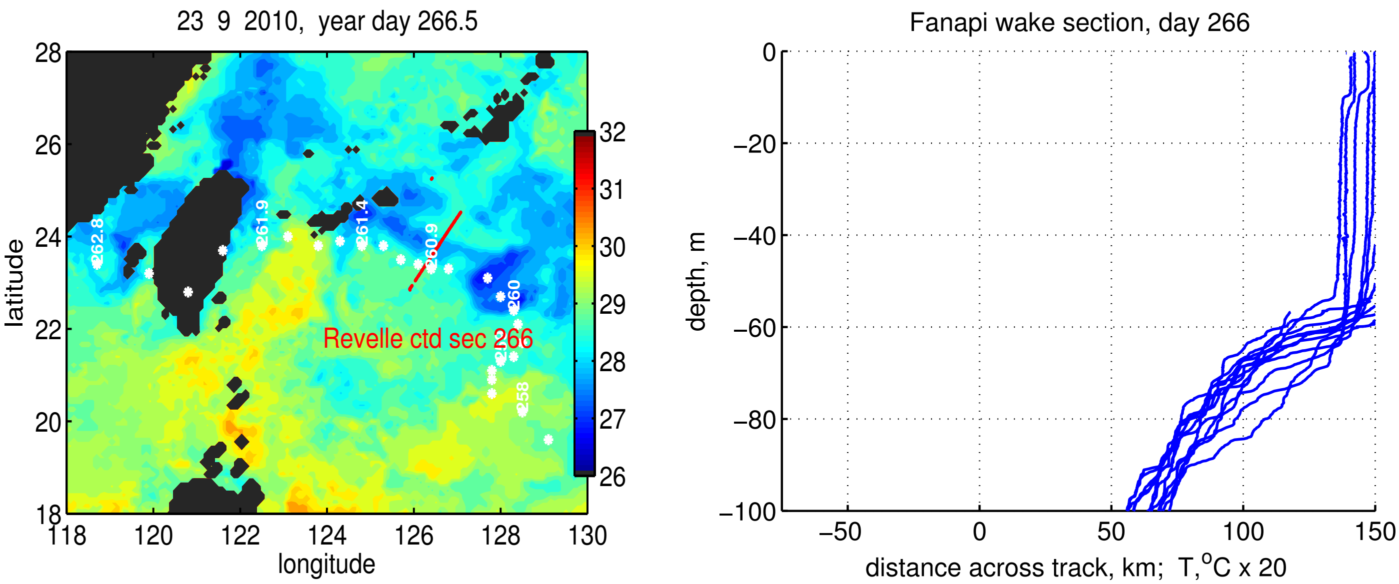

Figure 1: (left) An SST image and the track of typhoon Fanapi. The R/V Revelle ran a ctd section across the typhoon track and the cool wake on day 266, about six days after the passage of Fanapi. (right) Temperature profiles across the track. The cool wake occupied about the middle third of this section. Note the thin, warm surface layer above the cool wake. This is direct evidence of the (thin) warm layer hypothesized in H2.

warming consistent with H2. Even more striking, the heat content anomaly is clearly associated with the cool wake (Fig. 2, middle), consistent with H1. Said a little differently, the cool wake warms preferentially because it is relatively cool, and so has reduced heat loss (the sum of sensible, latent and net long wave radiative fluxes). The shallow trapping depth, 5 - 15 m, is consistent with the depth of diurnal cycling, which was pronounced on many days post-typhoon passage.

Impact/Applications

These two hypotheses on the mechanism of wake warming when combined with a heat budget lead to a simple, explicit solution for the e-folding time of the SST cool anomaly (Price et al., 2008),

$$\Gamma = C_1 \frac{\tau}{\lambda Q_n^{1/2}} \tag{1}$$

where τ is the wind stress magnitude, λ is known from air-sea transfer formula and is proportional to the anomalous heat flux associated with the cool SST anomaly, and Q_n is the amplitude of the diurnal maximum of the air-sea heat flux. There are no free constants in this model; the parameter $C_1 = 2.7 \times 10^{10}$ kg$^{1/2}$ m sec$^{-3/2}$ C^{-1} is a product of known thermodynamic constants and a factor

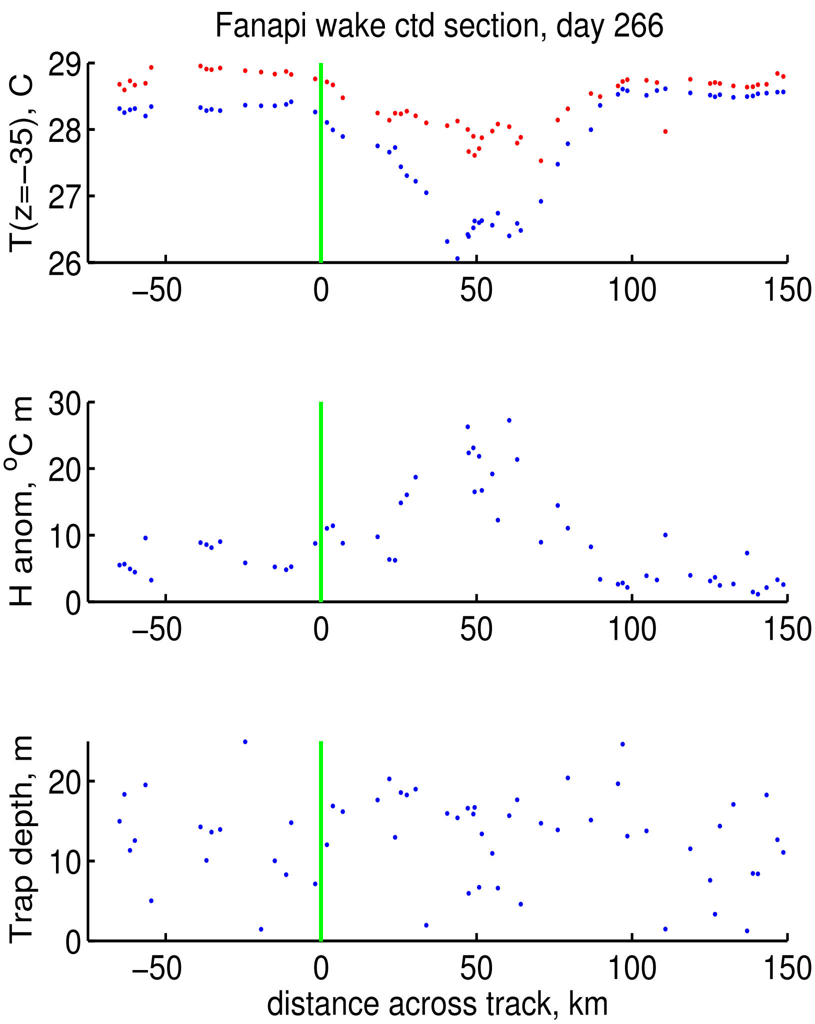

Figure 2: Temperature profile properties from the day 226 ctd section across the track of Fanapi. (upper) The SST and the 35 m temperature (red and blue dots). The cool wake is clearly evident as the cool anomaly centered about 50 km to the right of the track, denoted by the vertical green line. Notice that SST had warmed by almost 1.5 C by the time of this section. (middle) The heat content anomaly with respect to 35 m depth. Notice that the anomaly is very clearly correlated with the cool wake. This is direct confirmation of H1 of the warming model. (lower) The trapping depth, heat content anomaly divide by the surface temperature anomaly. This depth shows quite a lot of variability, about 5 to 15 m over the coolest part of the wake, but is consistent with the expectations of diurnal cycle mean and variability (Fig. 1, right).

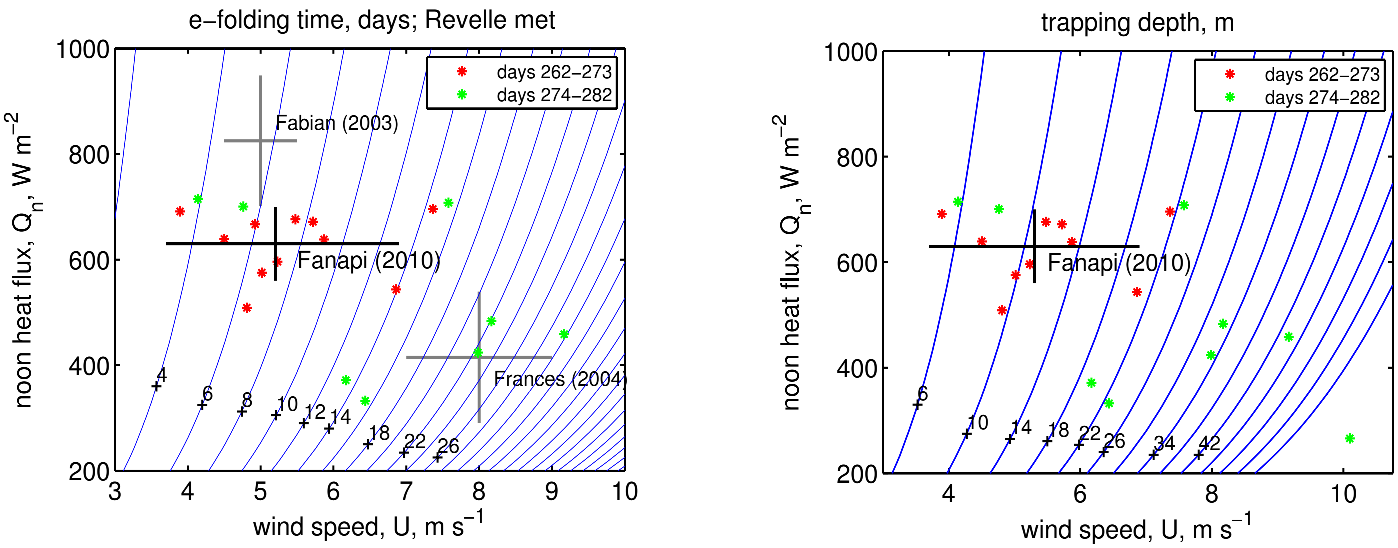

Figure 3: (left) The e-folding time (days) of a cool anomaly subject to the wind amplitude and noon maximum heat flux shown as the independent coordinates. The conditions appropriate for CBLAST hurricanes Fabian and Francesare shown, along with daily values (red and green dots) for the post-Fanapi period of ITOP. The e-folding time predicted by Eqn. (1) is shown as the background, contoured field, and is about 7 days for the period post-Fanapi. This is in good agreement with the observed e-folding time. (right) Trapping depth, the mean depth value of the temperature anomaly and a direct estimate of the warm layer thickness.

involving the latitude. When plotted in Fig. 3 the stress is represented as $\tau = \rho_a C_d U_{10}^2$ with the drag coefficient $C_d = 1.3 \times 10^{-3}$.

The solution (1) for e-folding time compares well with the CBLAST examples, giving an e-folding of about five days for Fabian and about 20 days for Frances (Fig. 3, left). It offers an explanation why the Frances case was somewhat different post-Frances weather was somewhat disturbed, cloudy and windy partly because of other nearby hurricanes, and the SST recovery was delayed mainly by greater that typical winds.

The ITOP Revelle shipboard meteorological data make possible a high quality estimate of the surface heat flux and the wind speed required to evaluate the wake warming model Eqn. (1) in the Fanapi case (the red and green dots of Fig. 3). The predicted e-folding time, roughly one week during the first ten days, is in reasonably good accord with the e-folding estimated from satellite imagery and from ocean observations (Mrvaljevic et al, Evolution of the cold wake of Typhoon Fanapi; personal communication and paper in progress). What was missing from the CBLAST cases was the *in situ* data required to know how deep below the sea surface this warming was actually occurring, 5 - 15 m (Fig. 2, lower). In this regard, the ITOP insitu data sets are unmatched.

This problem/phenomenon, hurricane wake warming, can be viewed as a test case for warming the ocean surface generally. The key finding here is that the relevant heat flux is made up of two components: a slowly varying mean, here represented by λ, and the diurnally-varying heat flux, here represented by the noon maximum, Q_n. The former determines the trend of surface temperature, and the latter determines the amplitude of the warming by setting the depth over which the mean heat flux is absorbed (i.e., the heat capacity of the ocean surface). The daily average heat flux alone is not sufficient to predict the depth over which the heat flux will be absorbed. This has direct implications for ocean modelling and thermodynamics.

Collaborations in the Coming Year

The ITOP data analysis noted above will continue into 2013. There are several important data types that can be used to investigate wake warming and that will be folded into the analysis centered to now on Revelle shipboard data. These include: 1) surface drifters, Luca Centurioni and Jan Morzel, 2) sea gliders, Luc Rainville, and 3) surface moorings, Ya-Ting Chang.

A collaboration with Prof. I-I Lin of National Taiwan University has resulted in a paper, Lin et al., Nature, 2012, describing an index that serves to forecast tropical cyclone intensity given knowledge of the upper ocean. The new piece of this is the understanding that the relevant property of the ocean temperature profile is the *average* of the temperature over the upper roughly 100 m (or to the bottom if in shallow waters) (Price et al., 2008). This is the effective SST that underlies a mature TC, and so is the relevant SST for heat and moisture fluxes that help fuel a TC. This new index goes a long ways toward reducing the large bias in TC intensity computed by the usual potential intensity index, and offers the means to make better TC intensity forecasts. This is perhaps the most direct and tangible result of research aimed at understanding and ultimately forecasting ocean/typhoon interaction.

A second ongoing collaboration involves a postdoctoral student from Lin's NTU group, Dr. Iam-Fei Pun. He has just started a postdoctoral year at WHOI under sponsorship of an ONR ITOP grant (to Steve Jayne) and under the supervision of Price and Jayne. Dr. Pun will be working to adapt his ocean thermal analysis scheme to the North Atlantic ocean. The idea is to combine satellite sea surface height (SSH) observations with satellite SST observations to infer the upper ocean thermal structure. The statistical connection between SSH and upper ocean thermal structure is deduced from ARGO profile data. The surprising result from Pun's work on the western North Pacific is that this statistical connection shows very substantial geographic variability associated with basin scale hydrographic and circulation features, e.g., the eddy rich zone associated with the subtropical counter-current is quite different from the Kuroshio extension. When completed, this analysis should yield an improved means to now-cast the upper ocean thermal field, including the

depth-averaged temperature relevant to ocean/TC interaction noted above.

References

Lin, I-I., P. Black, J. F. Price, C-Y. Yang, S. S., Chen, C-C. Lien, P. Harr, N-H. Chi, C-C. Wu and E. A. D'Asaro, 'An ocean cooling potential intensity index for tropical cyclones', *Nature*, under review, September, 2012.

Price, J. F., J. Morzel and P. P. Niiler, 'Warming of SST in the cool wake of a moving hurricane', *J. Geophys. Res.*, **113**, C07010, 2008. doi:10.1029/2007JC004393.

Price, J. F., 'Metrics of hurricane-ocean interaction: depth-integrated or depth-averaged ocean temperature? Ocean Sci., 5, 351-368, 2009. Available online at http://www.ocean-sci.net/5/351/2009/os-5-351-2009.html